

A Numerical Modeling Framework for Cohesive Sediment Transport Driven by Waves and Tidal Currents

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LONG-TERM GOALS

To develop a robust multi-phase, multi-class numerical modeling framework for both cohesive and non-cohesive sediment transport in the fluvial, estuarine and coastal environments.

OBJECTIVES

1. Developing a 3D turbulence-resolving numerical model for fine sediment transport in the oscillatory boundary layer in order to understand how turbulence-sediment interactions can determine the state of muddy seabed (transport modes).
2. Studying the attenuation of turbulence due to the presence of sediment via the interplay between sediment-induced density stratification and enhanced viscosity (rheological stress).
3. Extending the existing turbulence-resolving numerical study to coarser grain (sand) and poly-dispersed (e.g., size, density and shape) transport based on four-way-coupled Eulerian and Euler-Lagrangian numerical frameworks.

SIGNIFICANCE

Understanding various modes of sediment transport and the resulting transport rate driven by waves and currents are critical to better predictions of hydrodynamic, seabed properties, morphodynamics in the coastal environments. Through an enhanced/reduced bottom friction due to seabed processes, hydrodynamics and seabed dynamics become highly coupled and large-scale numerical models must incorporate appropriate parameterizations on seabed dynamics. For example, in our ongoing numerical modeling work to predict the hydrodynamics through the New River Inlet (NC) using a quasi-3D circulation model NearCoM-TVD, the computed magnitude of ebb tidal current can increase by 40 percents when bottom drag coefficient C_d is decreased from typical value used for surf zone (0.01) to that for estuary (0.003). In other words, it is critical to improve our capability to quantify and characterize seabed dynamics in order to provide reliable prediction of flow intensity in critical areas. In muddy environments, the role of bottom mud state in determining the hydrodynamic dissipation remains unclear. For example, one of the key findings resulted from AMASSEDS (e.g., Nittrouer et al. 1991) indicates significant reduction of bottom drag coefficient as tidal currents propagate over muddy seabed (Beardsley et al. 1995) due to damping of turbulence via sediment-induced density stratification (Kineke et al. 1994). On the other hand, field and analytical studies

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on wave propagation over muddy seabed (e.g., Sheremet & Stone 2003; Elgar & Raubenheimer 2008) report significantly increased energy dissipation due to the presence of bottom fluid mud. The observed vast difference on hydrodynamic dissipation appears to be related to a diverse range of muddy seabed state revealed by recent studies through detailed turbulence-resolving simulations (Ozdemir et al. 2010) and field observations (Traykovski 2010; Sahin et al. 2012).

APPROACH

A general modeling framework appropriate for a wide range of grain size (or Stokes number) and sediment concentration must be based on a multiphase flow formulation. For fine sediment transport in the muddy environments, the Stokes number of cohesive sediment particles (primary particles or flocs) is typically much smaller than 1.0 and the Equilibrium Eulerian Approximation (Balachandar & Eaton 2010) can be adopted. This approximation allows algebraic representation of particle velocity without solving the momentum equations of particle phase, and hence significantly reduces the complexity of the numerical scheme. This simplified formulation is similar to treating the effect of sediment on carrier flow as stratified flow with additional consideration of settling velocity, particle inertia, and rheology/sediment diffusivity due to inter-particle interactions. To greatly reduce the uncertainties in the turbulence closure for sediment-laden flow, a 3D turbulence-resolving simulation tool is developed in this study. The numerical model extends a 3D pseudo-spectral Navier-Stokes solver with high numerical accuracy (Cortese & Balachandar 1995) to study the role of sediment-induced density stratification in determining the resulting fine sediment transport and bed states in the wave boundary layer (Ozdemir et al. 2010, 2011). Because pseudo-spectral scheme is only suitable for simulation with constant viscosity, since 2012 we extended the work of Ozdemir et al. (2010) by replacing the original Chebyshev polynomial expansion in the wall normal direction with a sixth-order compact finite difference scheme. With this extension, we successfully used the new model to study the effect of enhanced viscosity on turbulence attenuation (in conjunction with the well-known sediment-induced density stratification mechanism) during fine sediment transport in steady channel flow and oscillatory flow (Yu et al. 2013a,b).

So far, this model has been used as a diagnostic tool to study fine sediment transport. To move toward a more realistic turbulence-resolving simulation model to accurately predict cohesive sediment transport, we need to further include the effect of particle inertia, hindered settling and net erosion/deposition to the bottom boundary. Implementing these new capabilities has been the main task of 2013. Since early 2012, we have also initiated a new research effort to develop turbulence-resolving numerical models for coarser grain (sand) and poly-dispersed (e.g., size, density and shape) transport in the four-way-coupled Eulerian and Euler-Lagrangian numerical frameworks.

WORK COMPLETED AND MAIN RESULTS

3D turbulence-resolving simulation of fine sediment transport: We begin by investigating wave-induced mud transport in energetic muddy shelf, such as that in the inner-shelf of Eel River where the Stokes Reynolds number of the wave boundary layer is around $Re_\Delta=1000$ (Traykovski et al. 2000). Our simulation results reveal the existence of four flow modes (or possible seabed states, Ozdemir et al. 2010) of wave-induced fine sediment transport due to the variation of sediment availability for a fixed settling

velocity (~ 0.5 mm/s) : 1) a well-mixed sediment concentration with no modulation in turbulence in very dilute flow (~ 1 g/L or smaller), 2) formation of sharp sediment concentration gradient in the water column, i.e., lutocline, at near bed sediment concentration of $O(1\sim 10)$ g/L. The flow above the lutocline is quasi-laminar due to damping of turbulence by sediment-induced stable density stratification but flow below the lutocline remains turbulent, 3) nearly laminar profiles throughout the entire wave boundary layer of both the sediment and fluid phases but followed by burst events due to shear instability during flow reversal. This occurs at near bed concentration of several tens per liter, 4) at $O(100)$ g/l or greater, a complete laminarization throughout the wave cycle. The existence of these flow modes has critical implications to our capability in assessing the muddy seabed states and various applications related to fluid mud transport. For instance, mode I represents a significantly confined, but highly mobile transport close to the seabed. Understanding the transition between mode I and mode II allow us to estimate the amount of offshore fine sediment transport via wave-supported gravity-driven mudflows (e.g., Traykovski et al. 2000). Moreover, mode III and IV represent much less energetic and less mobile fluid mud condition. Field observation suggests when modes III and IV occur, large surface wave damping rate is expected. In our recent work (Ozdemir et al. 2011), we also demonstrated the existence of these modes for a range of settling velocity under the same sediment availability and wave intensity ($Re_\Delta=1000$). Our ongoing work focuses on less energetic wave condition, similar to that at Atchafalaya inner-shelf, in the range of $Re_\Delta=400\sim 800$. Our goal is to develop a criteria for the transition between mode II and mode II (or IV), i.e., a saturation condition for wave-induced fluid mud for a range of Reynolds number.

Our preliminary results to simulate fine sediment transport at Stokes Reynolds number $Re_\Delta=600$ indicate very different picture of flow modes comparing to those of $Re_\Delta=1000$. The most important difference to be noted here was that for all cases simulated to be in mode II, the boundary layer can be turbulent for quite a long time but eventually laminarizes (becomes mode IV). We believe what we observed here is closely related to the strong transitional nature of wave boundary layer at such low Reynolds number in conjunction with turbulence modulation. In the classic work of Jensen et al. (1989) on laboratory observation of oscillatory boundary layer, the entire range of $Re_\Delta=500\sim 3460$ is categorized to be “intermittently turbulent”. With additional complication due to the damping of turbulence by sediment, the transitional nature of turbulence in the intermittently turbulent regime is further aggravated by the presence of sediment. Hence, it is necessary to revisit the clear fluid oscillatory boundary layer in the range of $Re_\Delta=500\sim 1000$ so that a more systematic and detailed picture on the sediment-free, intermittently turbulent regime can be obtained before we can confidently explain the sediment-laden condition.

Simulation results show that nonlinear growth plays a critical role on the instability at $Re_\Delta=500$ and 600. However, the nonlinear growth does not warrant sustainable transition to turbulence and depends on the amplitude and spatial distribution of the initial velocity disturbance. Simulation results at $Re_\Delta=500$ confirms that the flow mainly experiences linear hydrodynamic instability (see Figure 1a) and even for artificially large initial disturbance, the observed nonlinearity is weak (see Figure 1b) and subsequent transitional flow eventually decays. At $Re_\Delta=600$, nonlinear growth recurs at every wave period but such transition does not evolve into fully developed turbulence at

any time in the wave cycle. It is until $Re_\Delta=700$, the flow shows features of fully developed turbulence during some cycles but the transitional character of $Re_\Delta=600$ presents during other wave cycles. Therefore we conclude that flow in the range of $Re_\Delta=600$ to 700 to be classified as **self-sustaining transitional flow**. For higher Reynolds number the flow indeed exhibits the features of fully developed boundary layer turbulence for a portion of the wave period, which is known as the intermittently turbulent regime in the literature. Based on what we learn here for clear fluid flow, we hypothesize that when we simulate $Re_\Delta=600$ with significant sediment load, damping of turbulence may effectively reduce Re_Δ to be close to 500 and hence flow eventually laminarizes. A manuscript regarding the transitional nature of wave boundary layer at low Re_Δ was recently submitted for publication. A manuscript discussing the effect of sediment on the resulting flow modes at lower Re_Δ is currently in preparation.

The interplay between turbulence and enhanced viscosity: To further investigate the interplay between the collapses of turbulence, the rapid settling of sediment associated with laminarization, and the initiation of rheological stress due to the rapid increase of sediment concentration near the bed, we extend the numerical model of Ozdemir et al. (2010, 2011) with capabilities of modeling rheological stress. Comparing to the model results without rheology, we find that the present Newtonian rheological stress with an enhance viscosity tends to attenuate more turbulence and eventually trigger earlier laminarization. Laminarization further causes more significant settling, higher sediment concentration accumulated near the bed, and finally results in enhanced hydrodynamic dissipation. Our preliminary finding that rheology encourages laminarization may explain why large attenuation of surface waves over muddy seabed is ubiquitous and the highest dissipation rate is often observed during the waning stage of a storm (A. Sheremet (U. Florida) and P. Traykovski (WHOI), personal communications). Our work on fine sediment transport in the wave boundary layer and the effect of rheology was presented in the International Conference on Coastal Engineering 2012. This paper was selected by the Coastal Engineering Research Council (CERC) of ASCE as outstanding contribution to the conference. Two manuscripts reporting our findings on the effect of enhanced viscosity during fine sediment transport in steady channel flow and oscillatory flow are currently in press.

IMPACT/APPLICATIONS

Our modeling work reported here are directly related to past and ongoing ONR research programs, such as MURI wave-mud interaction and Tidal flat DRI. Ongoing extension of the turbulence-resolving numerical model for transport of coarser sediments and poly-dispersed transport are directly relevant to RIVET I & II where the seabed is mainly sandy or mixed sand-mud environments.

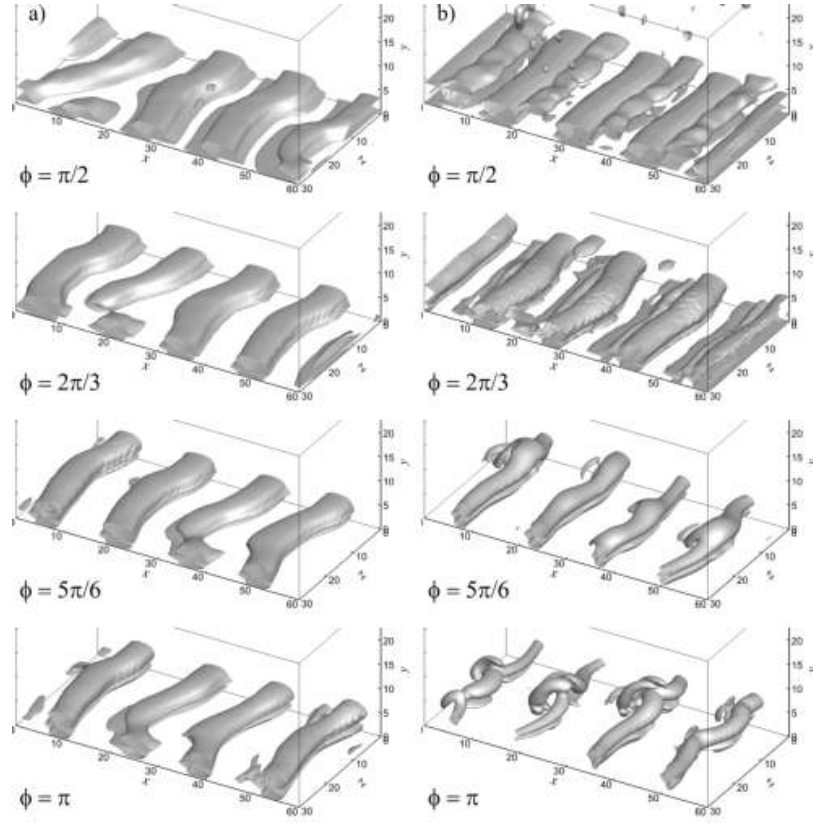


Figure 1: Vortex structures identified from the iso-contours of λ_{ci}^2 (Zhou et al. 1999) from $\phi = \pi/2$ to $\phi = \pi$ at $Re_\Delta=500$ for (a) low initial disturbance (b) large initial disturbance. In (a), 2D horizontal rollers do not evolve into 3D coherent structures at the end of the cycle. In (b), when large initial disturbance is specified, rollers eventually evolve into some weak 3D structures at the end of the cycle right before they get wiped out.

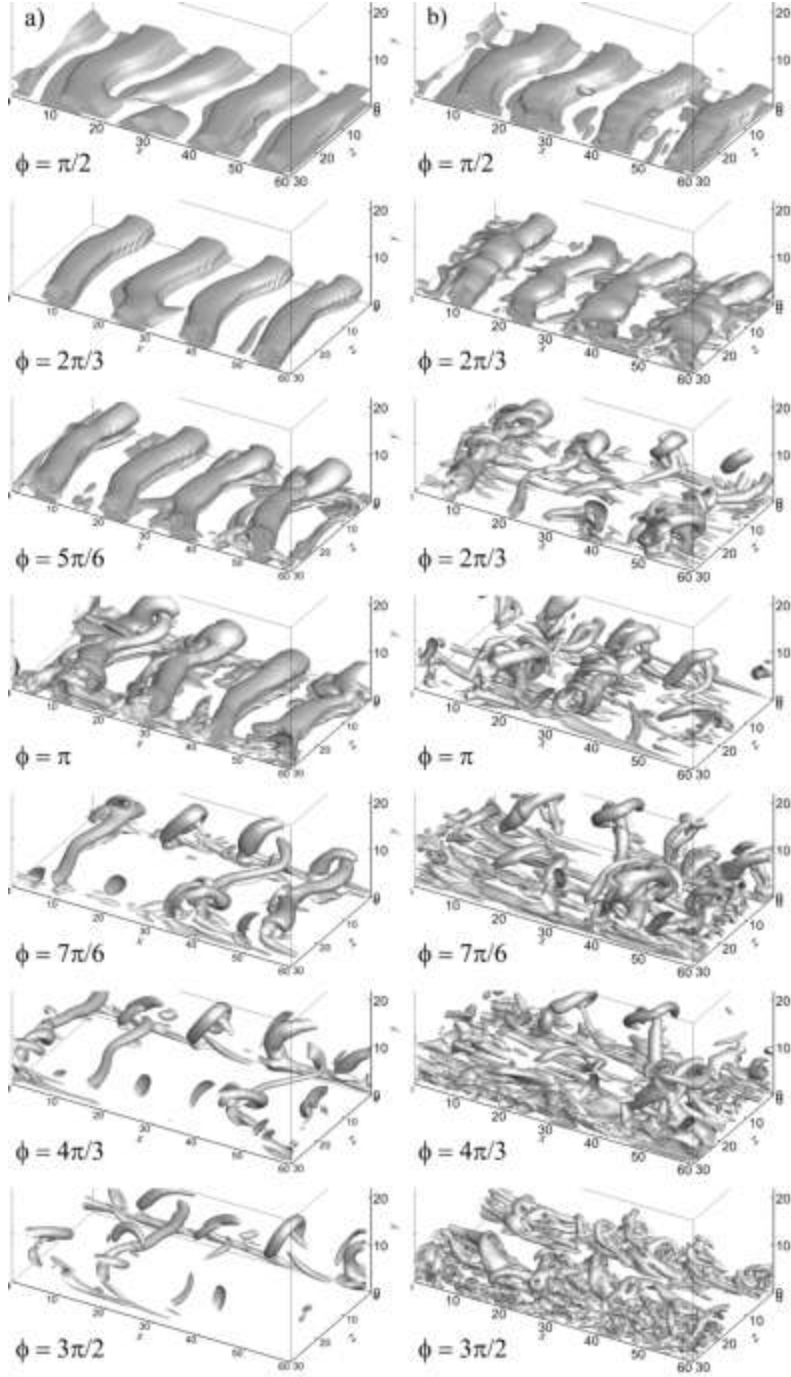


Figure 2: Vortex structures identified from the iso-contours of λ_{ci}^2 (Zhou et al. 1999) from $\phi = \pi/2$ to $\phi = \pi$ at $Re_\Delta=600$ for (a) low initial disturbance (b) large initial disturbance. In both cases, 2D horizontal rollers quickly evolve into 3D coherent structures. Although these 3D coherent structures are generated through nonlinear growth and are chaotic, spectral analysis suggests no fully developed turbulence is observed (no -5/3 slope) at any given time.

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